

# **Measurements of Wave-Induced Fluctuations in Underwater Radiance under Various Surface Boundary Conditions**

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## **LONG-TERM GOALS**

This project is part of the Radiance in a Dynamic Ocean (RaDyO) program which aims at developing an understanding of variability in underwater radiance distribution and its relation to dynamic processes within the ocean-atmosphere boundary layer.

## **OBJECTIVES**

The principal objective of our project is to measure wave-induced fluctuations in underwater light field under various sea-surface boundary conditions. The specific objectives include the characterization of wave-induced fluctuations in downwelling irradiance and radiance as a function of various environmental parameters such as wind/wave conditions, sky radiance distribution, direction of radiance observation, depth of observation, and water optical properties. Because of the complexity of the problem and multiplicity of factors affecting the light field fluctuations, achieving a comprehensive characterization of all these effects is unrealistic within the timeframe of the RaDyO program. Our study will focus on selected problems and environmental factors as the project progresses throughout the phase of main field experiments. The central theme of our study is to characterize light fluctuations at shallow depths caused by surface wave focusing under clear skies. The focusing events are the most intense fluctuations that occur on temporal scales of a fraction of a second.

The primary objectives for this reporting period were focused on the execution of two major field experiments, first the test experiment at the Scripps Pier in January 2008, and second, the main RaDyO experiment on FLIP and KILO MOANA in the Santa Barbara Channel in September 2008.

## **APPROACH**

The central idea of our project is to conduct in situ measurements of high-frequency fluctuations in underwater light field produced by surface waves under various boundary conditions. Our approach towards this objective builds largely on our past research experience in the area of wave-induced light fluctuations. This experience allowed us to define technical requirements for developing a suite of sensors whose design is optimized for measuring high-frequency light fluctuations. In particular, the measurements of wave-induced fluctuations in the underwater light field performed in the past (e.g.,

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Dera and Stramski, 1986; Stramski, 1986) showed a need for radiometer that is capable of sampling the light field over a large dynamic range at frequencies as high as 1 kHz.

With regard to the development of the radiometer system, which was the main objective during the previous reporting periods, our approach is based on the concept of multiple sensors mounted in a unique geometry to ensure measurements of both the downwelling irradiance and downwelling radiance distribution as a function of zenith angle  $\theta$  within two orthogonal azimuthal planes  $\Phi$ . The design includes twenty three light sensors. Most sensors measure radiance at a single waveband (532 nm). Up to seven sensors can be used to measure downwelling plane irradiance at different wavelengths (365, 410, 443, 488, 532, 610, and 670 nm). Radiance sensors are distributed within two azimuthal planes that are perpendicular to one another. The radiance sensors are based principally on a Gershun-tube design and are equipped with a collimating optics, an interference filter (532 nm), and a custom-built photodiode detector with appropriate parameters for our purposes. All sensors are characterized by very fast response enabling sampling of the underwater light field with a frequency of up to 1 kHz over several orders of magnitude. This is a unique feature because typical radiometers used today in oceanographic research do not satisfy requirements for such high-frequency measurements. In addition, the underwater unit is equipped with a depth sensor, temperature sensor, compass, and a rotator that allows us to control the spatial orientation of radiance sensors with respect to azimuthal direction. Most work on the development of the new instrument, which we refer to as the Underwater Porcupine Radiometer System (UPRAS), was completed and described during the previous reporting periods. The general view of UPRAS is shown in Fig. 1.

Our approach to conduct field experiments involves the acquisition of time-series data (typically 10-min time-series) of light field fluctuations at various depths with a 1 kHz sampling rate. The typical 10-min time-series includes 600,000 data points for each sensor. These data are acquired at depths ranging from about 0.5 m to 20-30 m. Most measurements are taken at shallow depths within the top 5 m of the ocean where wave-induced light fluctuations are most intense. The actual strategy for acquiring the data in the field is adjusted during experiments depending on variations in environmental conditions (wind, waves, sky conditions, etc.). This strategy may, for example, consist of the acquisition of successive time-series over a prolonged period of time (hours) at a single depth (e.g., 1 m) or a change of the measurement depth after every 10-min time series. With regard to data analysis, our approach involves the use of various statistical methods for the analysis of stochastic processes. The traditional analysis of random processes provides several statistical characteristics of light fluctuations such as statistical moments, probability density function, and frequency spectral density function. Special methods, referred to as the threshold analysis, are also used to provide the statistics describing the frequency of wave-focused pulses of light and duration of pulses.

This project is conducted in collaboration with the Institute of Oceanology, Polish Academy of Sciences (IOPAS) and the new instrumentation was developed at IOPAS. The key participants in the project from IOPAS are Dr. Miroslaw Darecki and an electro-optical engineer Mr. Maciej Sokolski.

## **WORK COMPLETED**

The Scripps Pier Test Experiment was carried out from January 6 through January 28, 2008. Our team in this experiment consisted of Dr. Darecki and Mr. Sokolski from IOPAS and myself. In this experiment we tested the deployment and performance of the newly developed porcupine radiometer (Fig. 2), we identified technical issues for refinements and improvements, and we addressed the

RaDyO science objectives for shallow coastal environments by acquiring more than 150 data files, each representing time series measurement over 10-20 min time period. These data were processed including data quality control, calibration, merging the radiometer data with compass data, and conversion to ASCII format. Data processing and analysis were focused on irradiance measurements because the radiance data were limited by insufficient control of azimuthal orientation of UPRAS due to the lack of steady currents in the near-shore zone at the Scripps pier. Our irradiance data were made available to all RaDyO participants through the RaDyO website: <http://www.opl.ucsb.edu/radyo/index.html> with a direct link to the web data directory at IOPAS: <http://www.iopan.gda.pl/~darecki/radyo/>. Based on the data analysis and instrument performance during the Scripps Pier experiment, additional laboratory tests were carried out to improve the instrumentation. In particular, the electronic noise which normally occurs due to interference of electromagnetic field generated by power suppliers, other instruments, or any electric infrastructure in the vicinity of experiment, was greatly reduced to negligible level. Also, the dependency of the radiometer 'dark' voltage  $U_{\text{dark}}$  on temperature  $T$  was examined in detail. Good correlation and stability of the relationship was observed, and a new linear relationship between  $U_{\text{dark}}$  and  $T$  was established. These results are now incorporated in data processing to achieve the best possible signal-to-noise ratio, which is especially important under low light conditions. In addition, after the Scripps Pier experiment, new cosine collectors for irradiance sensors were fabricated to extend the spectral range of our measurements into the UV region. These improvements were completed before the main experiment in the Santa Barbara Channel in September 2008.

In September 2008 we participated in the first main RaDyO experiment on FLIP and KILO MOANA in the Santa Barbara Channel. Our team consisted of two groups. The first group, Dr. Mirosław Darecki and Mr. Maciej Sokolski from IOPAS, was working on FLIP. They conducted radiometric measurements of light fluctuations with UPRAS as well as other hyperspectral radiometric measurements of time-averaged light field characteristics with several TRIOS sensors (Fig. 3). The measurements with the TRIOS sensors will provide, for example, the hyperspectral data of the average cosine of underwater light field, an apparent optical property characterizing the angular distribution of light field. During the period of the deployment of FLIP, radiometric measurements were made during 10 days. Overall, nearly 230 time-series of light field fluctuations were collected. Our second group on KILO MOANA included Dr. Ruediger Roettgers from Germany who brought his Point-Source Integrating Cavity Absorption Meter, a new graduate student in my lab, Selda Yildiz, and myself. During the cruise we operated the CTD-rosette system and we measured the absorption and scattering properties and particle size distribution (PSD) of discrete water samples. In collaboration with Drs. Svein Vagle and Oliver Wurl, we also made unique experiments to characterize PSD and optical properties of surface microlayer. This is an example of spontaneous initiation of new collaboration at sea with potentially original and important results of interest to the RaDyO program. While our activities on FLIP are funded by the RaDyO program, all our research activities on KILO MOANA are not supported by the RaDyO program nor any other grant or agency. I decided to provide this additional contribution to the field experiment in the Santa Barbara Channel because the RaDyO program had no plan for the analysis of discrete water samples. Such analysis provides essential data to support the interpretation of in situ optical measurements.

At the end of the reporting period, we prepared a poster entitled "An Underwater Porcupine Radiometer System for measuring high-frequency fluctuations in light field induced by sea surface waves" to be presented at the Ocean Optics XIX conference.

## RESULTS

The test experiment at the Scripps pier showed generally very good performance of our newly developed Underwater Porcupine Radiometer System (UPRAS). However, testing of the capability for azimuthal orientation of UPRAS was limited because of the lack of steady currents in the near-shore zone at the Scripps pier. The performance of our porcupine instrument deployed from FLIP during the Santa Barbara Channel experiment was excellent. However, several issues and limitations associated with the use of FLIP emerged during the experiment, which deserve special attention before the next RaDyO experiment to be conducted in 2009 off Hawaii Islands. First, the deployment and recovery of UPRAS from FLIP was difficult and not satisfactorily safe. This was caused by insufficient vertical distance between the boom and the deck from which the deployment/recovery of UPRAS took place. Second, FLIP exhibited significant movement on short time scales (seconds to minutes), primarily rotational movement within the horizontal plane. Although this may have been caused by inadequate mooring of FLIP in the Santa Barbara Channel, this issue made it very difficult or impossible for us to acquire 10-min time-series during which the radiance sensors maintained constant azimuthal orientation. Third, the use of our radiometric equipment at sea usually requires sporadic intervention to perform electronic tests or replace some critical parts of the sensors to execute experiments under a broad range of system configuration, for example various optical interference filters or different size of cosine collectors. The working conditions and space on FLIP appeared to be inadequate for these tasks because it is very difficult or impossible to do this type of work when the relatively large and complex instrument is placed on a very small deck exposed to weather conditions. Finally, FLIP was discharging waste into the ocean nearly continuously during the experiment. It is likely that this discharge had significant effect on the optical properties of seawater around FLIP where the measurements were taken. We feel that this is a major issue that needs to be addressed before the next RaDyO experiment.

Data collected during the Scripps Pier experiment show a characteristic rapid decrease in the intensity of wave-induced fluctuations of downwelling irradiance with an increasing depth (Fig. 4). In the presented example, the coefficient of variation of irradiance decreases from about 65% at a depth of 0.5 m to 10% at 5 m. These measurements were made under environmental conditions that favor strong wave focusing, that is under clear skies and weak winds. Under such conditions, measurements of time-series of downwelling irradiance show the presence of high-amplitude pulses of wave-focused light (Fig. 5). The highest pulses can exceed the time-averaged irradiance by a factor  $> 10$  at a depth of 0.5 m. The amplitude of wave-focused pulses and the high-frequency content of the irradiance signal are reduced with depth. With the increasing depth of observation, large changes are also observed in the probability density functions and frequency spectral density functions of irradiance fluctuations (Figs. 6 and 7). At the shallowest depths (0.5 - 1 m) the probability functions are highly asymmetric. The asymmetry decreases with depth as the probability density approaches Gaussian distribution at a depth of 5 m. We note that the rate at which this transformation occurs will depend on a number of environmental parameters, for example the optical properties of seawater. The result shown in Fig. 6 is representative of specific conditions during the measurements from the Scripps pier. The power spectra of irradiance fluctuations show significant contribution to the variance at frequencies above 1 Hz and a clear reduction of high-frequency content of the signal with depth (Fig. 7). Our data from the Scripps Pier experiment also reveal a characteristic decrease in the intensity of wave-induced fluctuations of downwelling irradiance with an increase in solar zenith angle (Fig. 8). The increase in solar zenith angle also results in a decrease in the asymmetry of the probability function of downwelling irradiance measured at shallow depths (Fig. 9).

Figure 10 shows examples of 20-sec time-series of downwelling radiance measured at different directions (zenith angle of observation) within the azimuthal solar plane at a depth of 1 m during the Santa Barbara Channel experiment in September 2008. These measurements were made from FLIP under clear skies when wave-focusing effects were relatively strong. Significant changes are observed in the intensity and frequency content of radiance signal as a function of the direction of observation. Interestingly, the highest pulse of wave-focused radiance exceeding the time-averaged radiance by a factor of about 40 is seen at a zenith angle of observation of 30 deg, which does not coincide with the mean angle of refracted solar rays underwater. The underwater zenith angle of refracted solar rays during the measurement was 24 deg.

The preliminary results shown in this report point to a wealth of novel information about the time-dependent underwater light fields, which we acquired during the first RaDyO experiments. For example, the very high amplitudes of wave-focused pulses of light as shown in Figs. 5 and 10 have never been reported in the past. These pulses represent the highest transient concentrations of solar energy that occur in nature, which likely have important implications to photochemical reactions within the near-surface layer of the ocean.

## **IMPACT/APPLICATIONS**

The major impact of this project will be to provide novel data and understanding of wave-induced fluctuations in underwater light field. This phenomenon has been scantily investigated in the past. Our measurements are expected to provide critical information for achieving science objectives of the RaDyO program, including the development and validation of time-dependent coupled surface wave-radiative transfer model. Our findings are also expected to have broader implications beyond the disciplines of ocean optics and physics, specifically in the areas of ocean biology and photochemistry.

## **RELATED PROJECTS**

This effort is related to other projects funded through the RaDyO program.

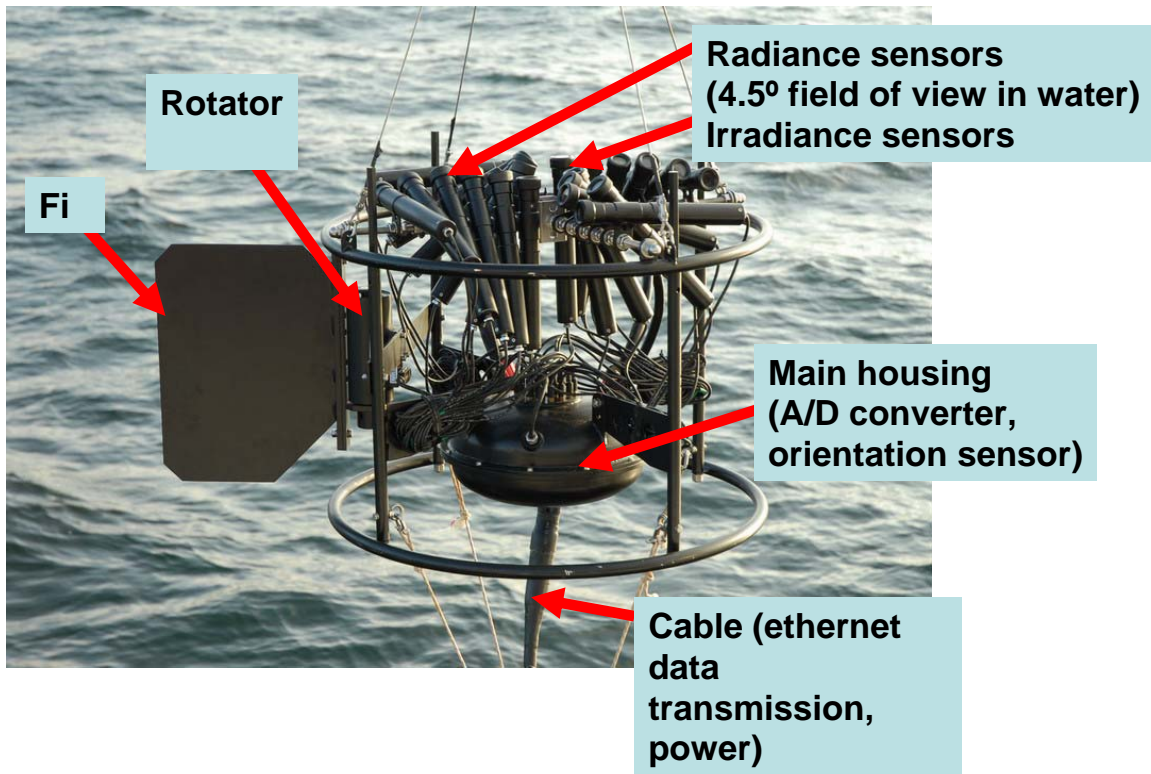
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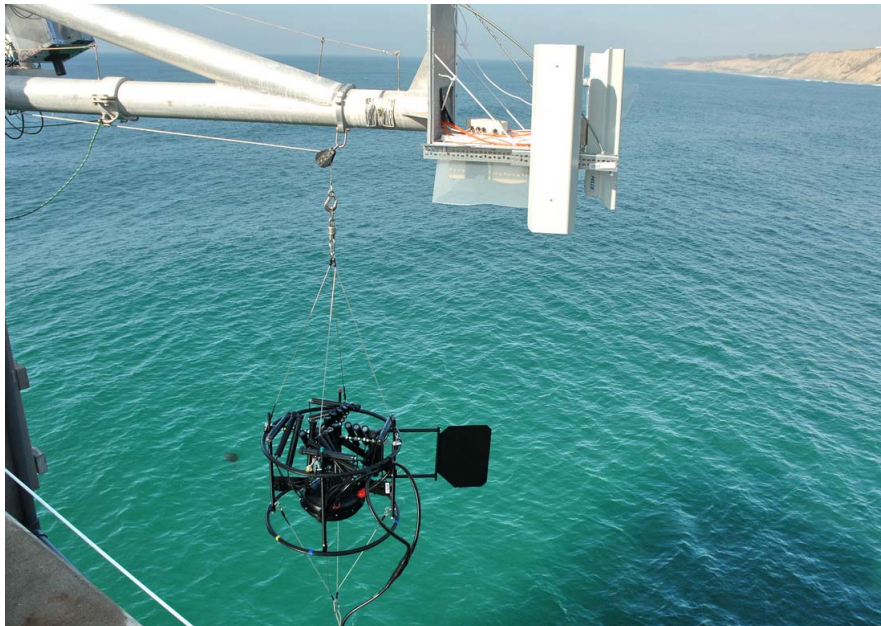
Stramski, D. 1986. Fluctuations of solar irradiance induced by surface waves in the Baltic. *Bulletin of the Polish Academy of Sciences, Earth Sciences*, 34, 333-344.

## **PUBLICATIONS**

None.



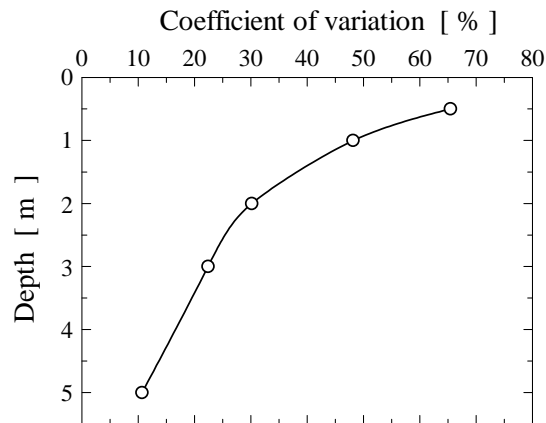
*Figure 1. A general view of the Underwater Porcupine Radiometer System.*



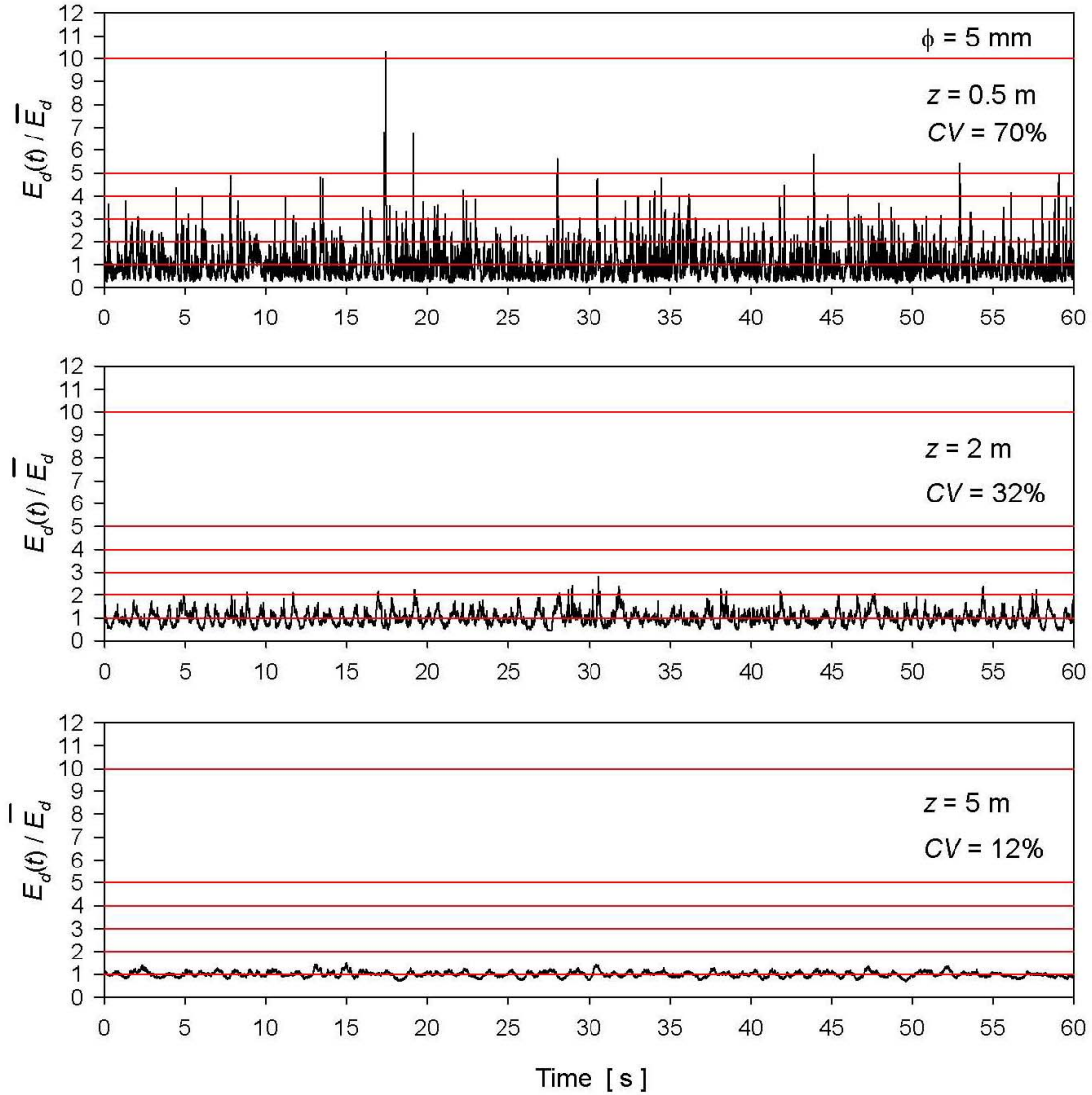
*Figure 2. Deployment of the Underwater Porcupine Radiometer System during the test experiment from the Scripps Pier in January 2008.*



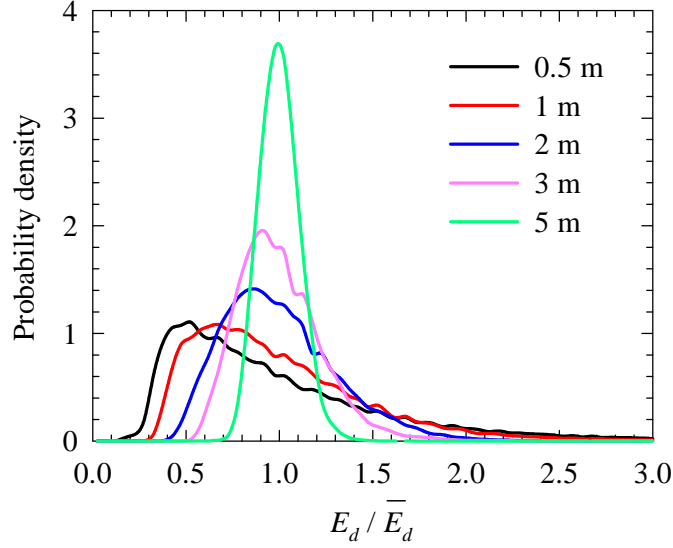
**Figure 3.** *Deployment of the Underwater Porcupine Radiometer System from FLIP during the experiment in the Santa Barbara Channel in September 2008.*



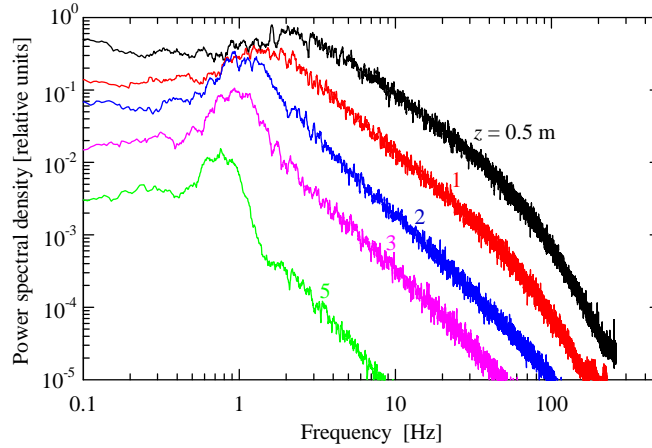
**Figure 4.** *Intensity of wave-induced fluctuations in downwelling irradiance shows a characteristic rapid decrease with depth. The presented vertical profile of the coefficient of variation was obtained from measurements of downwelling irradiance (at 532 nm) on a sunny day under weak winds during the Scripps Pier experiment.*



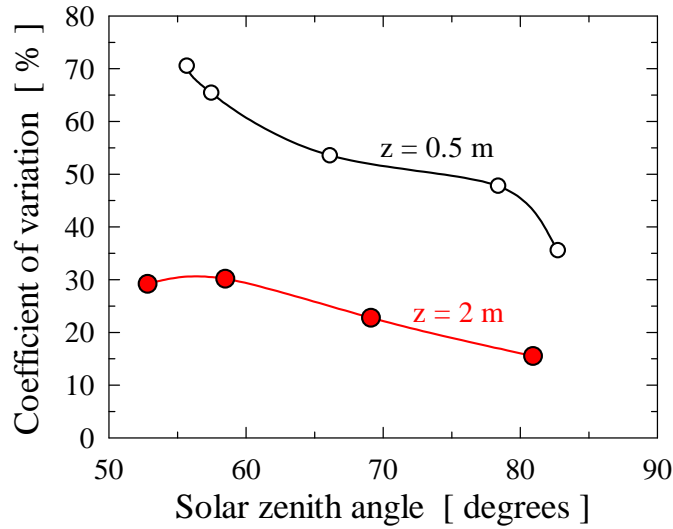
**Figure 5.** Wave-induced fluctuations in downwelling irradiance at shallow depths under sunny skies are characterized by the presence of high-amplitude pulses of wave-focused light, which can exceed the time-averaged irradiance by a factor  $> 10$ . The amplitude of wave-focused pulses and the high-frequency content of the irradiance signal are reduced with depth. The presented examples of 1-min time series of downwelling irradiance (at 532 nm) were measured at depths of 0.5 m, 2 m, and 5 m on a sunny day under weak winds during the Scripps Pier experiment. The instantaneous irradiance signal is normalized to the time-averaged irradiance. The diameter of cosine collector was 5 mm. The values for the coefficient of variation (CV) are also given.



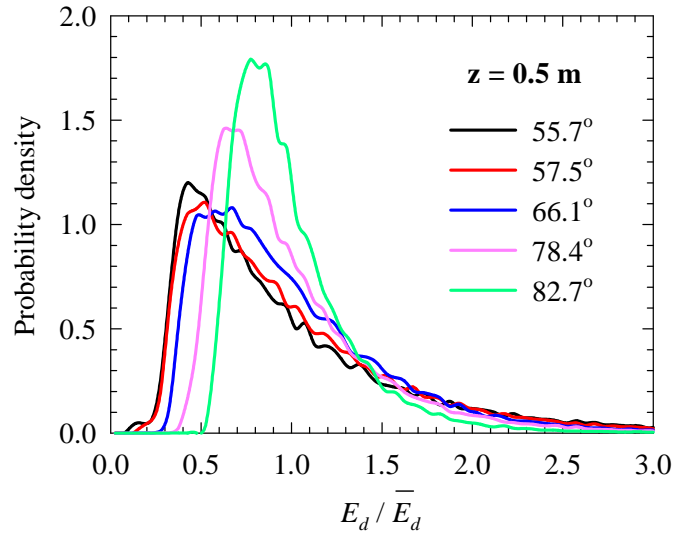
**Figure 6.** *Probability density functions of wave-induced fluctuations in downwelling irradiance are highly asymmetric at shallow depths under sunny sky conditions. The asymmetry decreases with depth as the probability density approaches Gaussian distribution. The presented examples of probability function were obtained from time-series of downwelling irradiance (at 532 nm) measured at depths of 0.5, 1, 2, 3, and 5 m on a sunny day under weak winds during the Scripps Pier experiment. The instantaneous irradiance signal is normalized to the time-averaged irradiance.*



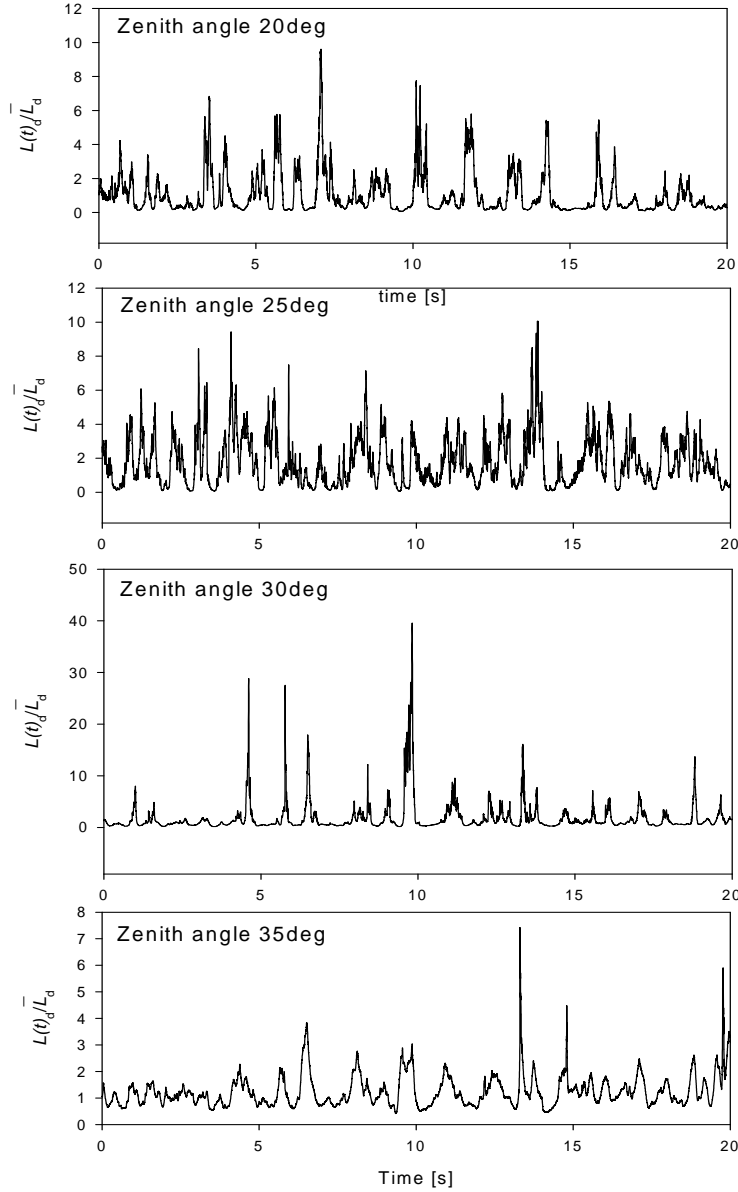
**Figure 7.** *Frequency spectral densities of wave-induced fluctuations in downwelling irradiance at shallow depths under sunny sky conditions show significant contribution to the variance at frequencies above 1 Hz. The high-frequency content of the irradiance signal decreases with depth. The presented examples of power spectra were obtained from time-series of downwelling irradiance (at 532 nm) measured at depths of 0.5, 1, 2, 3, and 5 m on a sunny day under weak winds during the Scripps Pier experiment.*



**Figure 8.** Intensity of wave-induced fluctuations in downwelling irradiance shows a characteristic decrease with an increase in solar zenith angle. The presented curves of the coefficient of variation as a function of zenith angle were obtained from irradiance (532 nm) measurements at two depths (0.5 m and 2 m) on a sunny day under weak winds during the Scripps Pier experiment.



**Figure 9.** Probability density functions of wave-induced fluctuations in downwelling irradiance at shallow depths under sunny sky conditions show a decrease in asymmetry with an increase in solar zenith angle. The presented examples of probability function were obtained from irradiance (532 nm) measurements at a depth of 0.5 m on a sunny day under weak winds during the Scripps Pier experiment. These measurements were made for different solar zenith angles increasing from  $\sim 56^\circ$  to  $83^\circ$ . The instantaneous irradiance signal is normalized to the time-averaged irradiance.



**Figure 10.** Significant changes occur in the intensity and frequency content of wave-induced fluctuations in downwelling radiance, which are measured at different directions at shallow depths under sunny conditions. The highest pulse of wave-focused radiance exceeding the time-averaged radiance by a factor of about 40 is observed at a zenith angle of observation of 30 deg, which does not coincide with the mean angle of refracted solar rays underwater. The presented examples of time-series of downwelling radiance at different directions (i.e., zenith angle of observation) within the azimuthal solar plane were measured at a depth of 1 m from FLIP during the Santa Barbara Channel experiment in September 2008. The underwater zenith angle of refracted solar rays during the measurement was 24 deg. The instantaneous radiance signal is normalized to the time-averaged radiance.